A FAST X-RAY TIMING CAPABILITY ON XEUS

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Abstract

The Rossi X-ray Timing Explorer (RXTE) has demonstrated that fast X-ray timing can be used to probe strong gravity fields around collapsed objects and constrain the equation of state of dense matter in neutron stars. These studies require extremely good photon statistics. In view of the huge collecting area of its mirrors, XEUS could make a unique contribution to this field. For this reason, it has been proposed to include a fast X-ray timing capability in the focal plane of the XEUS mirrors. We outline the scientific motivation for such a capability, present some sensitivity estimates, and discuss briefly a possible detector implementation.

Key words: Missions: XEUS – General relativity - Equation of state of dense matter – Black holes – Neutron stars.

1. Introduction

XEUS (X-ray Evolving Universe Spectroscopy) is proposed as a potential follow-up mission to XMM-Newton. The primary task of XEUS will be to perform spectroscopy of faint X-ray sources to trace the origins and evolution of hot matter back to the early ages of the Universe (see Hasinger et al.2000). To achieve this goal, XEUS requires a very large collecting area (> 20 m^2, Bleeker et al. 2001).

The X-rays generated in the inner accretion flows around black holes (BHs) and neutron stars (NSs) carry information about regions of the strongly curved space-time in the vicinity of these objects. This is a regime in which there are important predictions of general relativity still to be tested. High resolution X-ray spectroscopy and fast timing studies can both be used to diagnose the orbital motion of the accreting matter in the immediate vicinity of the collapsed star, where the effects of strong gravity become important. The spectroscopic approach is already well covered by the XEUS detector baseline, but the fast timing one should also be considered. With the discovery of millisecond aperiodic X-ray time variability (QPO) from accreting BHs and NSs, and brightness burst oscillations in NSs, RXTE has clearly demonstrated that fast X-ray timing has the potential to measure accurately the motion of matter in strong gravity fields and to constrain masses and radii of NSs, and hence the equation of state of dense matter. With its huge collecting area, XEUS could provide an order of magnitude sensitivity improvement in timing studies over RXTE, if a fast X-ray timing capability is present in the focal plane. In the following we outline the additional exciting science XEUS could do with such a capability.

2. Summary of scientific objectives

2.1. Probing strong gravity fields

High-frequency QPOs have been seen in both BHs and NSs (see van der Klis (2000) for an extensive review). In BHs, the QPO models proposed invoke General Relativity (GR) effects in the inner accretion disk and depend strongly on the BH spin, making these QPOs effective probes of spacetime near the event horizon (see e.g. McClintock 1998). In NSs, three types of QPOs are commonly observed, ν_{LF}, 15–60 Hz, ν_1, 200–800 Hz and ν_2, 800-1200 Hz. In the relativistic precession model (Stella & Vietri 1998), ν_{LF}, ν_1, ν_2 observed across a wide range of objects are identified with three fundamental frequencies characterizing the motion of matter in the strong field as predicted by GR. The low-frequency QPO at ν_{LF} is thought to be due to *nodal precession*, dominated by the inertial-frame dragging predicted by GR in the vicinity of a fast rotating collapsed object. The lower frequency kHz QPO at ν_1 is identified with relativistic *periastron precession*. Unlike the relativistic effects seen in the orbit of Mercury and the relativistic binary pulsar PSR1913+16, for which weak field approximations apply, the periastron precession close to a collapsed star is dictated by strong field effects. Finally ν_2 is the orbital ("Keplerian") frequency; its value alone already restricts the allowed range of mass and radius of the NS (Miller, Lamb & Psaltis 1998). Other models rely on a beat-frequency interpretation for both ν_1 and ν_{LF} (Alpar & Shaham 1985; Miller, Lamb & Psaltis 1998), associate the observed frequencies with oscillation modes of a precessing accretion disk (e.g. Psaltis & Norman 2002). Alternatively, in the case of NSs, ν_1 could be associated with a Keplerian frequency at the outer radius of a boundary layer between the accretion disk and the NS surface, ν_{LF} with radial oscillations in the boundary layer, and ν_2 with a frequency of a Keplerian oscillator under the influence of the Coriolis force (Titarchuk & Osherovich 1999).

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With an order of magnitude better sensitivity, QPOs from a few Hz to 1600 Hz will be detected from many objects with a high enough significance to use the data for crucial tests. Regardless of the physical origin of the QPOs at ν_{LF} and ν_1, the increased sensitivity and range will have dramatic benefits. At higher frequencies, either strong signatures of the innermost stable circular orbit (ISCO), which sets an upper bound on ν_2, will be discovered from several sources (evidence has been found for one source so far: 4U1820-30, Zhang et al. 1998), or the frequencies themselves will allow the elimination of several candidate equations of state of dense matter (Miller, Lamb & Psaltis 1998). In the *relativistic precession* interpretation, there are several fundamental predictions yet to be tested. First, the epicyclic frequency $\Delta\nu = \nu_2 - \nu_1$ should fall steeply to zero as ν_2 increases and the orbital radius approaches the ISCO. The behaviour of the epicyclic frequency in the vicinity of BHs and NSs is dominated by strong-field effects and drastically different from any Newtonian or post-Newtonian approximation. Hence it provides a powerful test of the strong field properties of the metric (see Stella & Vietri 1999). According to the model $\Delta\nu$ should also decrease for low values of ν_2. Second, ν_{LF} should scale as ν_2^2 over a wide range of frequencies (until "classical" terms due to stellar oblateness become important). Observing such scaling would provide an unprecedented test of the $1/r^3$ radial dependence of ν_{LF} predicted in the Lense-Thirring interpretation (Stella & Vietri 1999).

In the above model, the QPO frequencies depend sensitively on the mass (M) and angular momentum (J) of the compact star, as well as on the radius at which the QPOs are produced. M and J could be independently estimated from waveform measurements at ν_2, thus overdetermining the problem so that the underlying theories can be tested in critical ways. The increased sensitivity of XEUS will enable QPOs to be detected within their coherence times. The cycle waveform, which it will be possible to reconstruct, depends on the Doppler shifts associated with the local velocity of the radiating matter in the emitting blob or spot, as well as on curved-spacetime light propagation effects. If the frequency ν_2 of the orbit is known, QPO waveform fitting yields the mass M (and Kerr spin parameter) of the compact object.

2.2. Equation of state of dense matter

Nearly coherent oscillations at ~ 300 Hz or ~ 600 Hz have been observed during type I X-ray bursts from about 10 NS so far (see Strohmayer 1998 for a review). These oscillations are probably caused by rotational modulation of a hot spot on the stellar surface. The emission from the hot spot is affected by gravitational light deflection and Doppler shifts (e.g. Miller & Lamb 1998). With XEUS, the oscillation will be detected within one cycle. The composition and properties of the NS cores have been the subject of considerable speculation, and remain a major issue in modern physics : at the highest densities, matter could be composed of pion or kaon condensates, hyperons, quark matter, or strange matter. By fitting the waveform, it will be possible to investigate the spacetime around the NS, and simultaneously constrain its mass and radius, and hence determine the equation of state of its high density core (see e.g. Nath, Strohmayer & Swank 2002).

2.3. Additional science

A fast X-ray timing capability would allow XEUS to investigate the physics of a wide range of astrophysical sources, such as accreting millisecond pulsars, micro-quasars, X-ray pulsars, dippers, CVs, Novae, Soft gamma-ray repeaters, Anomalous X-ray pulsars, ... For instance, there is only *one* accreting millisecond pulsar known: SAXJ1808-3658 (Wijnands & Van der Klis 1998; Chakrabarti & Morgan1998). Its properties suggest that all NS systems should show pulsations at some level. In most models, pulse amplitudes cannot be suppressed below $\sim 0.1\%$ (rms) without conflicting with spectroscopic or QPO evidence. With XEUS, the sensitivity to persistent millisecond pulsations will be well below this level (pulsations at the level of 0.01% rms would be detected in 1000 seconds in Sco X-1). Detection of such pulsations in objects also showing kHz QPOs and burst oscillations would immediately confirm or reject several models for these phenomena involving the NS spin (e.g. Miller, Lamb & Psaltis 1998). In addition, it has been suggested that such objects could be among the brightest gravitational radiation sources in the sky, emitting a periodic gravitational wave signal at the star's spin frequency (Bildsten1998). Undirected searches in frequency space for such radiation lose sensitivity because of statistical considerations. Independently measuring the spin period very accurately would therefore be of great importance for periodicity searches with gravitational wave antennae (e.g. Brady et al. 1997).

For micro-quasars, the link between the very fast disk transitions observed in X-rays and the acceleration process could be studied on very short time scales, allowing the non steady state disk properties and their link to the formation of relativistic jets to be explored (Belloni et al. 1997; Fender et al.1999). This would be of direct relevance to understanding the properties of AGNs, where presumably similar jet formation mechanisms operate on a much larger scales. In addition, through time-resolved spectroscopic observations, the spacetime close to the black holes could be probed using the variability of the iron Kα line.

3. XEUS sensitivity for timing studies

For the sensitivity computations, we have assumed the energy response of the XEUS mirrors as given in the last report of the telescope working group (Aschenbach et al. 2001). We have further assumed the proposed high energy

extension in which the inner mirror shells of the telescope are coated with supermirrors (the effective area is thus $\sim$ 20000 cm^2 at $\sim$ 9 keV and $\sim$ 1700 cm^2 at 30 keV). Finally we have assumed that the detector at the focal plane has a detection efficiency equivalent to 2 millimeters of Silicon. Table 1 gives the count rates expected from some sources.

Table 1. Examples of total count rates above 0.5 keV and above 10 keV ($C_{\rm E>10keV}$) in kcts/s. The X-ray burst input spectrum is a blackbody of 1.5 keV with a normalization yielding an Eddington luminosity at 8.5 kpc. SAXJ1808-3659 is the millisecond pulsar taken at the peak of its 1996 outburst.

Source name	XEUS-1	XEUS-2	$C_{\rm E>10keV}$
Crab	253	811	5
Sco X-1	1210	3840	180
GC X-ray burst	120	217	51
SAXJ1808-3659	34	135	2.5

Let us now compute the sensitivity to QPO and coherent signal detections. First, for a QPO, the signal to noise ratio n_σ at which it is detected in a photon counting experiment is approximately:

$$n_\sigma = \frac{1}{2}\frac{S^2}{B+S} r_S^2 \left(\frac{T}{\Delta\nu}\right)^{1/2}$$

where S and B are source and background count rate, respectively, r_S is the (rms) amplitude of the variability expressed as a fraction of S, T the integration time and $\Delta\nu$ the bandwidth of the variability. The bandwidth $\Delta\nu$ is related to the coherence time τ of a QPO as $\Delta\nu = 1/\tau$. On the other hand, for a coherent signal ($T<1/\Delta\nu$), the more familiar exponential detection regime applies, with false-alarm probability $\sim$exp$[-S^2 r_S^2 T/2(B+S)]$.

From the above formulae, assuming B $\sim$ 0 appropriate for XEUS, one can estimate the RMS amplitude corresponding to a 5σ QPO detection as a function of the source count rate (Figure 1). Similarly one can compute the RMS for the detection of a coherent signal at a given false alarm probability (Figure 2). These two plots demonstrate that with its huge collecting area XEUS provides an order of magnitude sensitivity improvements in timing studies over RXTE.

4. Detector implementation

The detector needs to be able to handle up to 3 Mcts/s (XEUS-1) and 10 Mcts/s (XEUS-2) (equivalent to a 10 Crab source, see Table 1) with a timing resolution of $\sim$ 10μs and a deadtime less than $\sim$ 0.1μs. Doing fast timing with good spectral resolution would strongly increase the sensitivity for timing studies. The energy resolution of the detector should therefore be good, ideally around 200 eV (i.e. a factor of $\sim$ 10 improvement over the RXTE/PCA). Finally the detector energy range should match closely the high energy response of the mirrors.

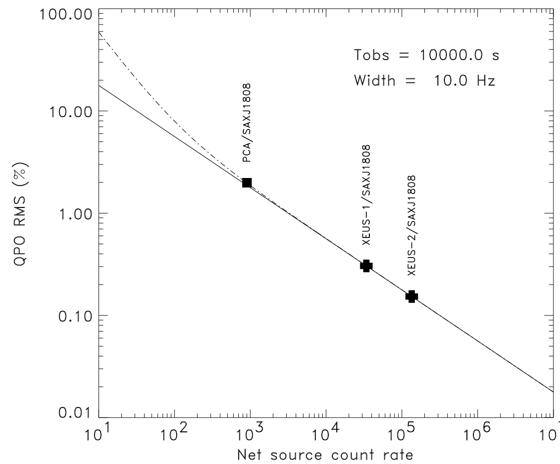

Figure 1. Comparison between the XEUS (solid line) and RXTE/PCA (dot-dashed line) sensitivity for QPO detection (5σ in 10 ksec, signal width 10 Hz). An illustrative example is provided by the millisecond pulsar for which RXTE failed to detect QPOs. As can be seen, a factor of $\sim$ 10 improvement in sensitivity over the RXTE/PCA is obtained with XEUS.

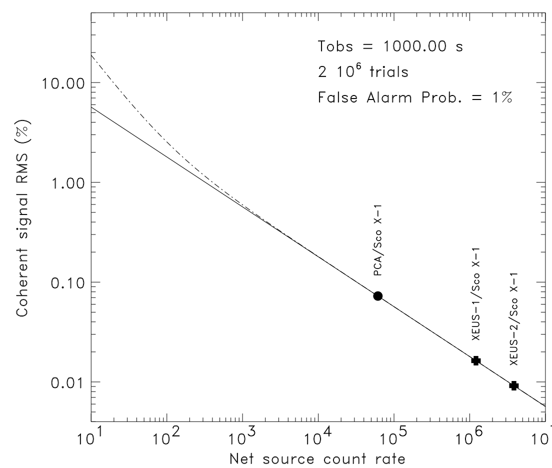

Figure 2. Comparison between the XEUS (solid line) and RXTE/PCA (dot-dashed line) sensitivities for coherent signal detection (1 ksec). The detection level corresponds to a false alarm probability of 1% for 2×10^6 trials. So far, no pulsations have ever been detected from Sco X-1. The XEUS sensitivity is 10 times better than the current RXTE/PCA sensitivity.

In the current XEUS detector baseline, the Wide Field Imager (WFI) has the highest count rate capabilities. However, even in the most optimistic case, it will only be able to provide timing information up to 500 kcts/s (by using a fast window mode). This means that an alternative solution should be considered. Among the fast X-ray detectors currently available, Silicon Drift Detectors (SDDs) are the most promising (Lechner et al. 2001). The fast X-ray capability for XEUS could be implemented with either a single

SDD at the focus, or a matrix of a few (~ 10) SDDs placed out of focus.

The SDD is a completely depleted volume of silicon in which an arrangement of increasingly negative biased rings drive the electrons generated by the impact of ionising radiation towards a small readout node in the center of the device. The time needed for the electrons to drift is much less than 1 μs. The main advantage of SDDs over conventional PIN diodes is the small physical size and consequently the small capacitance of the anode, which translates to a capability to handle high count rates simultaneously with good energy resolution. To take full advantage of the small capacitance, the first transistor of the amplifying electronics is integrated on the detector chip (see Fig. 3). The stray capacitance of the interconnection between the detector and amplifier is thus minimized, and furthermore the system becomes practically insensitive to mechanical vibrations and electronic pickup.

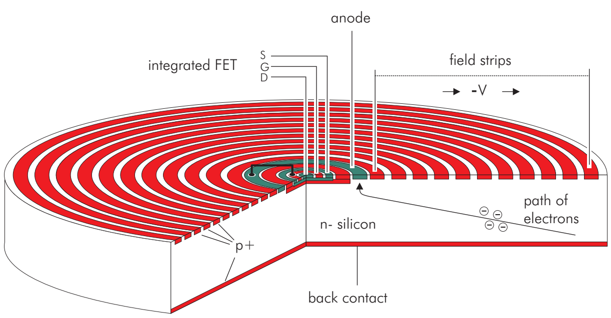

Figure 3. Schematic cross section of a cylindrical Silicon Drift Detector (SDD). Electrons are guided by an electric field towards the small collecting anode located at the center of the device. The first transistor of the amplifying electronics is integrated on the detector ship (drawing kindly provided by P. Lechner).

With short signal shaping times (250 ns), SDDs have been proved to be capable of handling count rates exceeding 1 Mcts/s with moderate pile-up. Energy resolution of better than ~ 200 eV (at 6 keV, equivalent to a low energy threshold ~ 0.5 keV) is readily achieved with low cooling (-20°C) for count rates below 10^5 cts/s (e.g. Lechner et al. 2001). With such a device, the fast timing capability would explore completely new windows of X-ray timing; first in the energy domain by getting below ~ 2.5 keV (current threshold of RXTE-like proportional counters) and in the frequency domain by reaching $\sim 10^4$ Hz (where signals have been predicted, Sunyaev & Revnivtsev 2000). SDDs are currently produced with thicknesses of 300 microns. Although there are on-going efforts to thicken these devices, the best match of the high energy response of the mirror could be achieved by associating the SDD detector with a higher density semi-conductor detector located underneath (e.g. CdTe, CdZnTe, GaAs). The device could be implemented independently of the WFI or integrated on the sides of it as a separate detector.

The requirements in terms of telemetry rate, power, mass, volume and cooling for the fast timing capability do not appear constraining for XEUS.

5. Conclusions

A fast X-ray timing capability on XEUS would nicely complement its primary science, at low cost. Probing strong gravity fields, constraining the equation of state of dense matter, and more generally studying the brightest sources with fast X-ray timing would become possible with XEUS. There are no technical issues: fast X-ray detectors capable of handling the expected count rates already exist.

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